An Introduction of the National Center for Photovoltaics (NCPV) at the National Renewable Energy Laboratory (NREL)

國家可再生能源實驗室
國家光電中心
簡介

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國家可再生能源實驗室(NREL)
及
國家光電中心(NCPV)的成立

Solar Energy Research Institute (SERI) – 1977

↓

National Renewable Energy Laboratory (NREL) – 1992

Photovoltaic (PV) Programs at
NREL + Sandia National Laboratory (SNL)

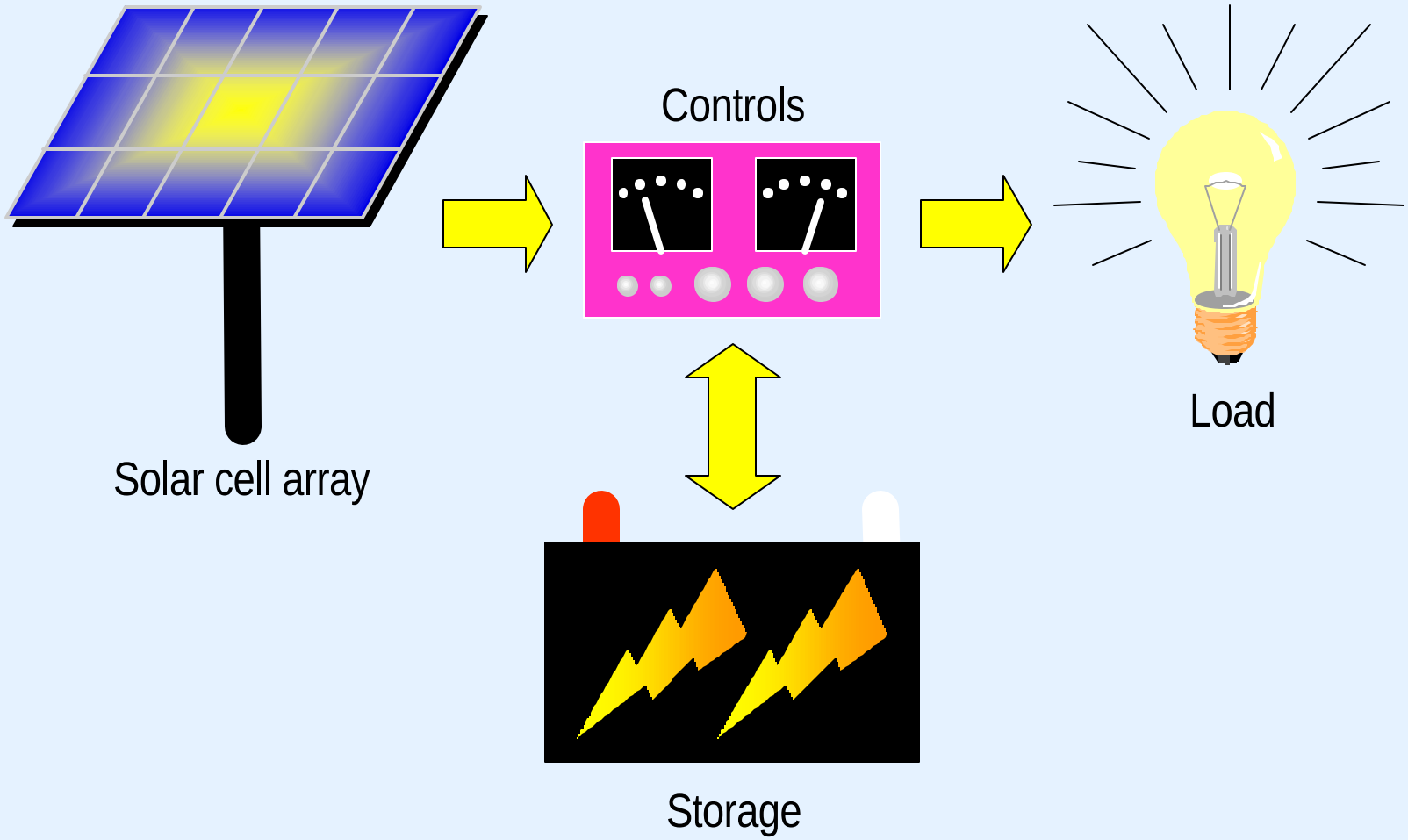
→ NCPV (1996)

NCPV Roles, Functions, Mission, and Vision

國家光電中心的
角色、功能、任務、及願景展望

- 提供戰略指導方向及整合美國國家實驗室、大學、PV工業界及領域的研發應用能力和容量。
- 強化加速光電相關工業技術的發展、和資源在長短期程中的調度與使用。
- 執行世界第一流的研發、促進合夥及成長的機會、提供討論及資訊的服務。
- 建立NCPV的世界領導地位、從實驗室的研發以發揮PV的潛能、到市場的擴展、使PV成功地成爲全球能源的重要資源。

Parts of a Typical PV System



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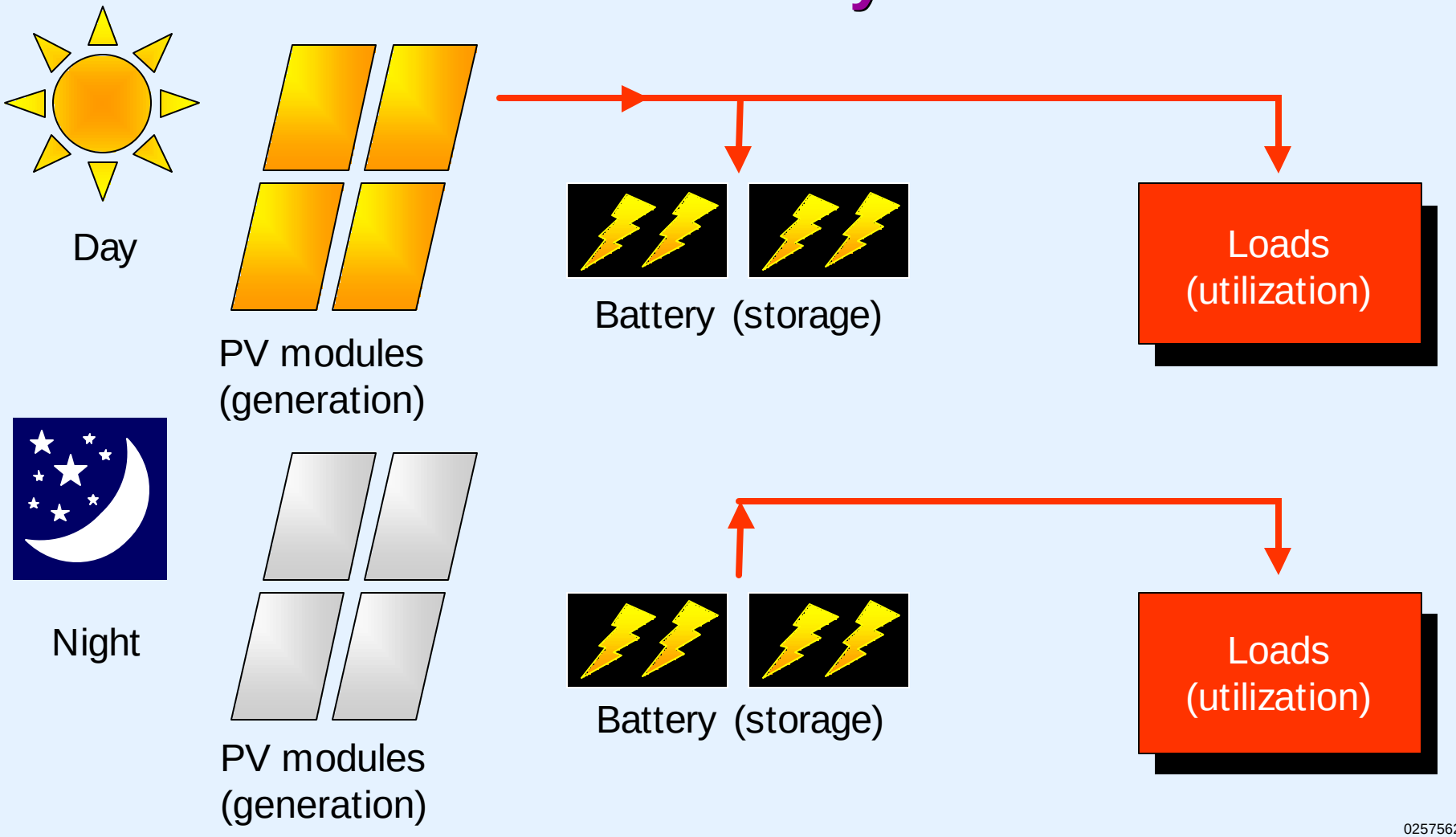
How a Photovoltaic System Works



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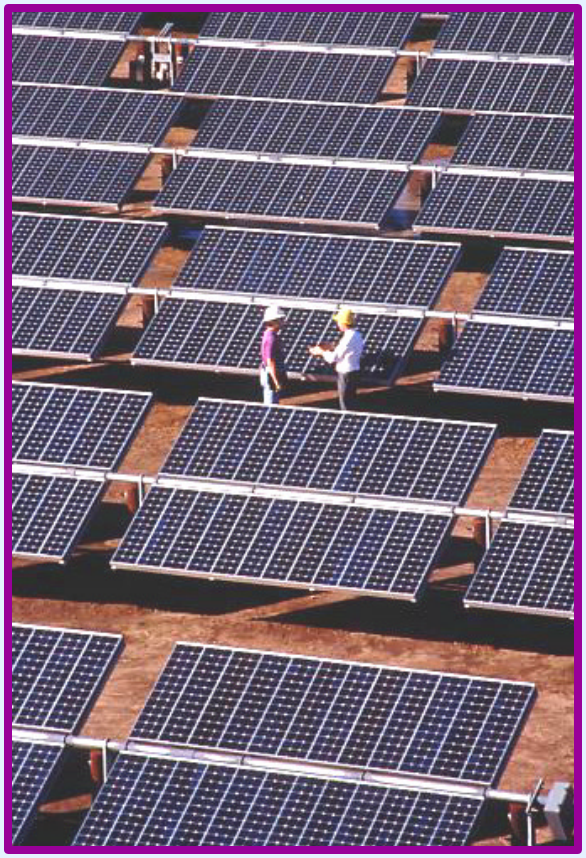
Photovoltaics (PV)

- Direct conversion of sunlight to electricity



Advantages

- Modular (mW to many MW)
- No (or few) moving parts
- Noise and pollution free
- Reliable; low operating costs
- Abundant, indigenous resource (30,000 km^2 PV for 700 GW)

PV的優點與經濟效益

與柴油發電機(diesel generators), 不可再充電蓄電池(primary batteries), 傳統的電力發電(conventional utility power), 和核能發電(nuclear utility power)比較, PV的優點與經濟效益可條列如下:

高度可靠性,安全性,及獨立自主性
高度裝置彈性(從開闊空地斜坡,建築物屋頂牆壁窗戶,到汽車皆可裝設)
高度模式擴充彈性(modular designs for scale up)
高度可運輸性(transportability)
高建設速度,低建設費用(因接近使用電力地點)
低操作費用及發電成本(免費燃料--太陽光)
低度維護需要
無污染無噪音發電
低度或無廢料處理需要(如核廢料運輸儲存)
低度或無社會和環境成本(如環境品質惡化,核幅射安全顧慮及反核示威)
新型中高科技工業可提升科技水準並提供就業及商業機會

當然, PV也有它的缺點. 比如單位面積發電電力密度(power density)較低, 初期投資成本高; 另外PV如應用在大規模發電, 比如100-500 MW(百萬瓦),可能需要的土地面積就會大, 但仍視使用的光電模板種類,效率,及模板支架物型設計而定.

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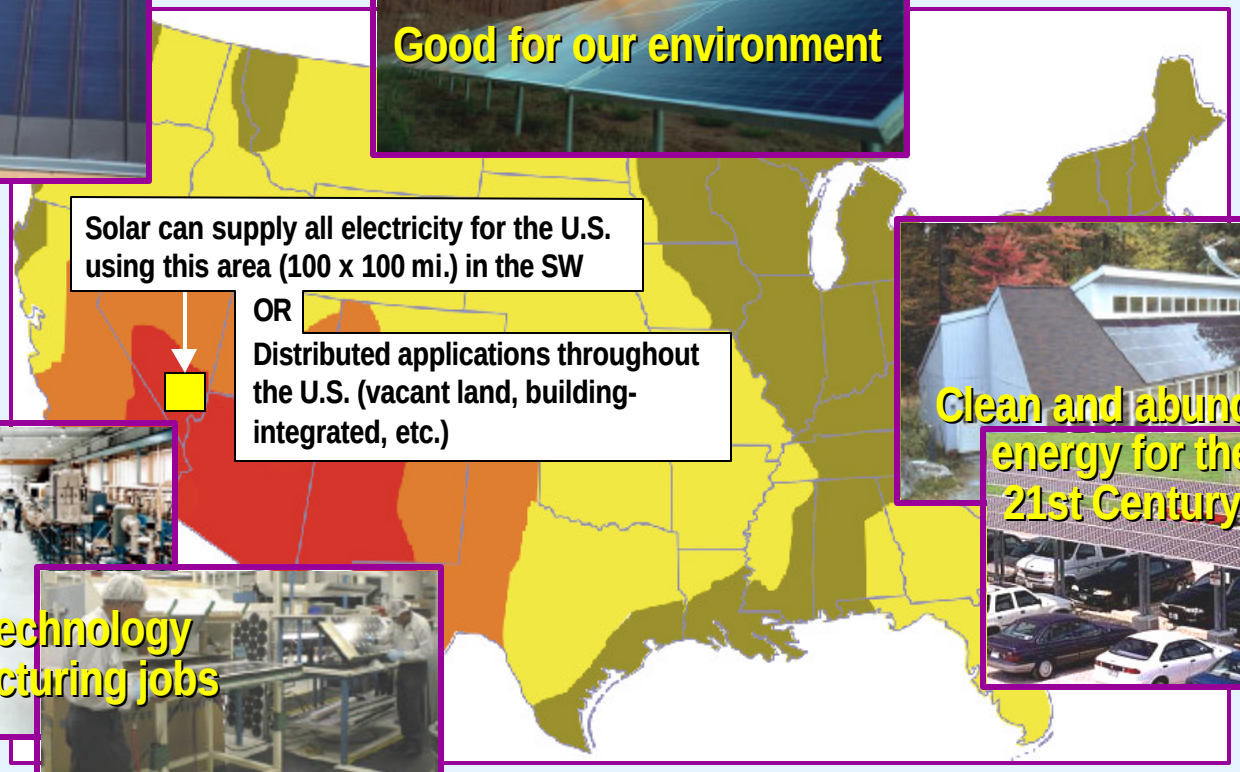
Photovoltaics is Solar Electricity

DOE PV Program Goal:
U.S. leadership in technology, industry, and markets



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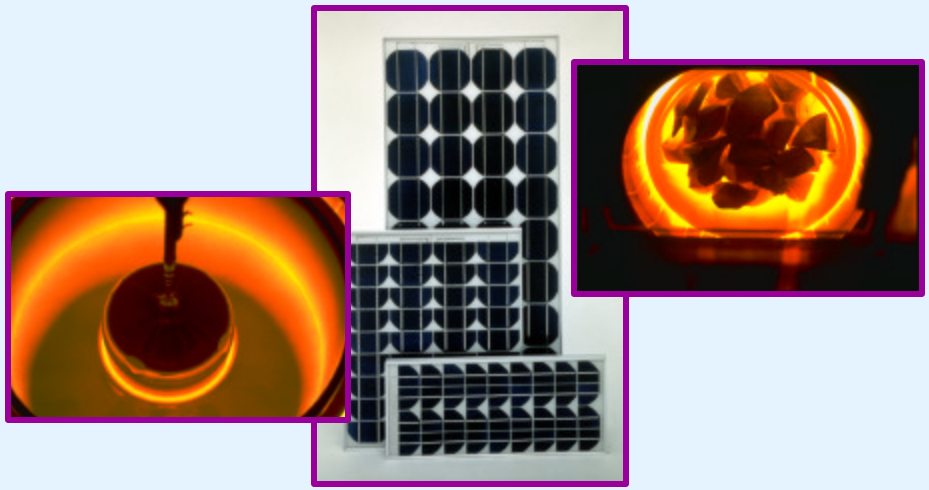
表一. 太陽能光電池 (Cells) 與光電板 (Modules) 已確認最高效率

半導體材料	太陽能光電池 (PV Cell, ~4 cm2)	太陽能光電板 (PV Module)
單晶矽 (c-Si)	24.0%	21.6% (862 cm2)
薄膜單晶矽 (thin film c-Si)	17.0%	
多晶矽 (pc-Si)	17.8% (1.0 cm2)	15.3% (1017 cm2)
非晶矽 (a-Si)	12.7% (1.0 cm2)	10.2% (903 cm2)
多晶薄膜CuInGaSe2	17.0% (0.4 cm2)	11.1% (938 cm2)
	13.9% (6.64 cm2)	9.7% (3883 cm2)
多晶薄膜碲化鎘 (CdTe)	15.8% (1.05 cm2)	8.1%(838 cm2); 7.8%(6838 cm2)
單晶砷化鎵 (GaAs)	25.1%	
薄膜砷化鎵 (GaAs)	23.3%	
單晶磷化銦 (InP)	21.9%	
聚光式單晶矽 (c-Si)	25.7% (1.21 cm2 @ 74 suns)	20.3% (1875 cm2 @ 80 suns)
聚光式單晶砷化鎵 (GaAs)	27.6% (0.126 cm2 @ 255 suns)	25.1% (41.4 cm2 @ 57 suns)

參考資料: M. A. Green et al., "Solar Cell Efficiency Tables (Version 5)," Progress in Photovoltaics: Research and Applications, Vol. 3, 51-55 (1995)

Crystalline Silicon (Ingot-Based) PV—Progress and Status



Key companies: BP Solarex, Siemens Solar, Kyocera, AstroPower, Solec/Sanyo, Sharp, Photowatt, Shell

- ~85% of today's market
- 150 MW capacity (to double in near-term)
- Proven products, 20-year warranties
- Large ingots: 100 kg CZ, 200 kg casting
- Multiple ingots w/ melt replenishment
- Wire saw: < 300 µm wafers, < 200 µm kerf

Efficiency Status	Cells	Modules
Float-zone	24.7	22.7
Czochralski	22.0	13–15
Cast poly	19.8	10–13

- Batch/continuous processing
- High-efficiency devices in production
- Well-developed technology base– new understanding of defects/impurities
- Continuous electromagnetic casting in production

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Crystalline Silicon (Non-Ingot-Based) PV—Progress and Status

Key companies: ASE Americas, Evergreen Solar, AstroPower, Ebara Solar, Bayer, Pacific Solar, Kaneka

- Status varies from prototype modules to pilot production to commercial products
- Proven products (~ 3% of market)
- Capacity increases underway– few tens of MW in near term

Efficiency Status	Cells	Modules
EFG	14–15	10–12
String ribbon	14–15	10–12
Thick Si/substrate	16.6	>10
Dendritic web	16–17	14
Thin Si/substrate	up to 11	n/a

- Improved performance from defect/ impurity and passivation studies
- New interest in thin silicon growth

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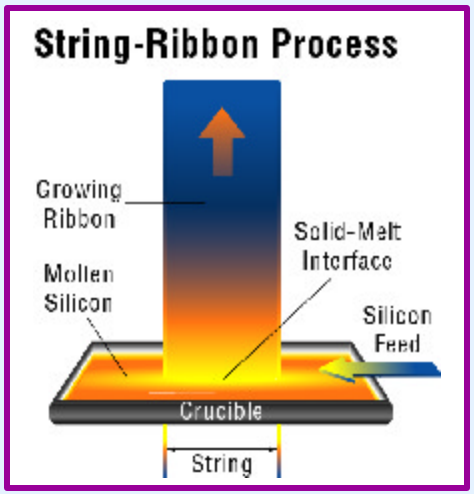
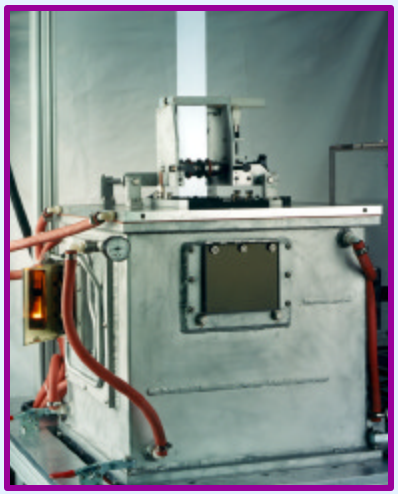
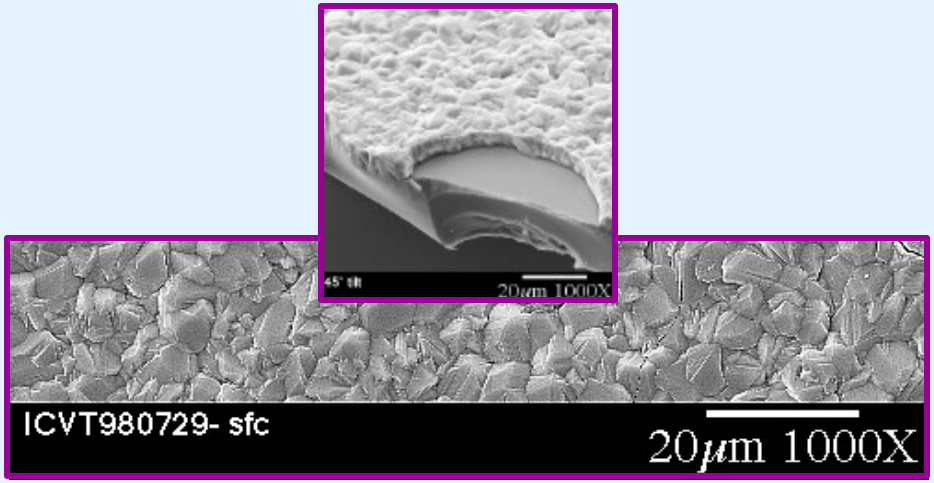
Crystalline Silicon (Non-Ingot-Based) PV— Research Issues and Directions



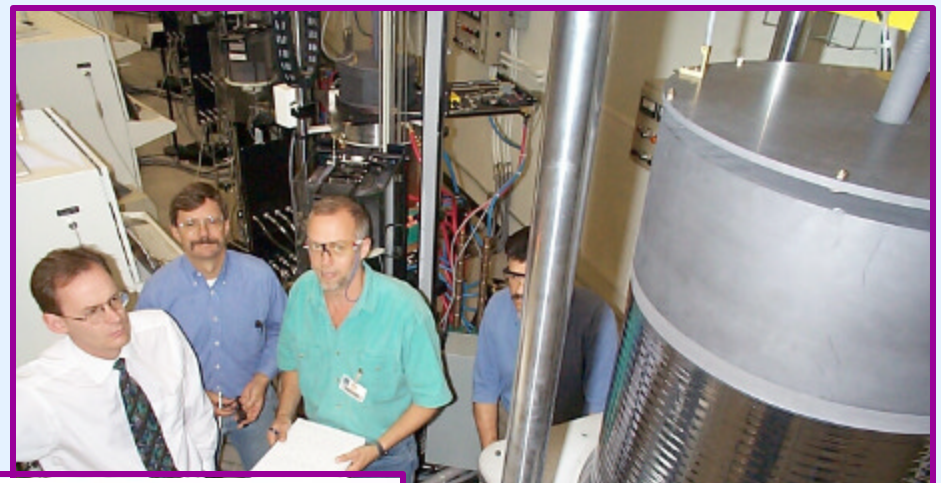




- Manufacturing yield and throughput
- Novel processing for continuous sheets
- Impurity/defect gettering and passivation
- New technology directions
  - ASE Americas – 1 m diameter cylinders
  - Evergreen – < 100 μm thick, wide ribbon
  - AstroPower – < 50 μm, monolithic interconnects on substrate

- Thin silicon on low-cost substrate
  - Fast deposition rate (> 1 μm/min)
  - Grain size comparable to thickness
  - Diffusion length greater than thickness
  - Insulating substrate for interconnects
- Many novel approaches: solid-state recrystallization, nucleation and growth, LPE, CVD, CVT, laser ablation, ...
- Orientation-independent processes for light-trapping and passivation in thin Si

EFG Silicon Cylinders — ASE Americas



Current: 0.5 m diameter
150 µm thick

Future: 1.0 m diameter
<100 µm thick

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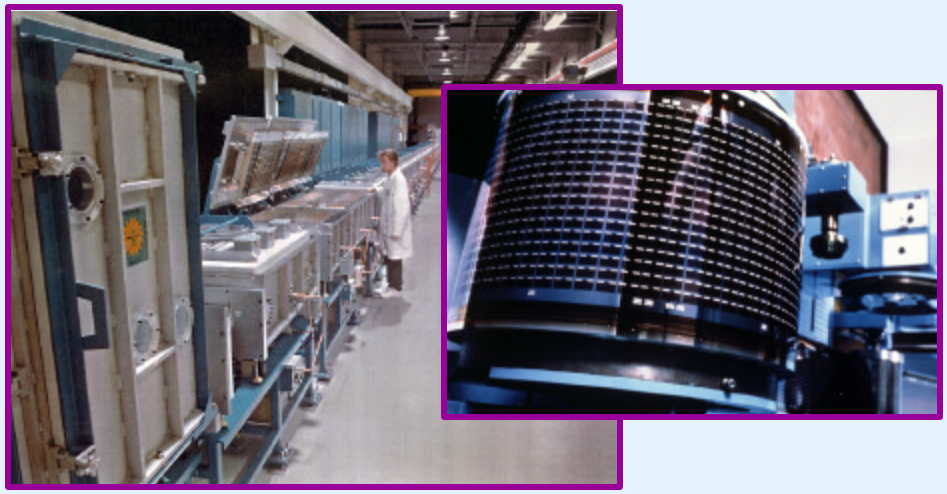
Thin-Film Amorphous Silicon PV—Progress and Status



Key companies: BP Solarex, United Solar/ ECD, EPV, Iowa Thin Films, Sanyo, Canon, Phototronics, DunaSolar

- Multi-MW/year in consumer products
- 5 and 10 MW plants operational; few tens of MW in near term
- Unique products for building integration (e.g., roofing, cladding)

Efficiency status: (stabilized)

Cell	12.7
Submodule	10.4
Module	7–8
Commercial	5–7

- Engineered "solution" for degradation: thin absorber layers and multijunctions
- Extensive fundamental research, leveraged by many other applications

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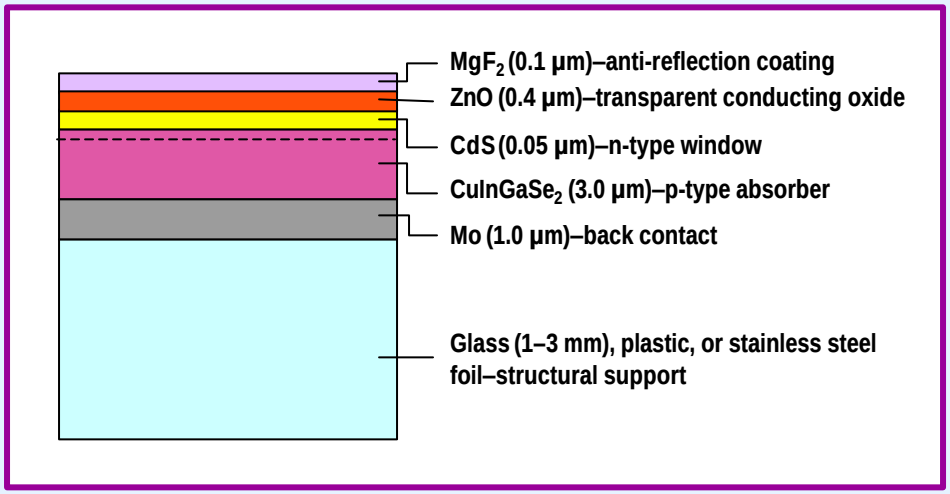
Thin-Film Copper Indium Diselenide (CIS) PV—Progress and Status



Key companies: Siemens Solar, Global Solar/ITN, ISET, EPV, Wurth Solar, Showa/Shell

- Prototype production started in 1998:
  - First commercial products (5–10 W)
  - Efficient, large modules (>12%)
  - Expansion to multi-MW in near term
- Field testing of modules shows promise; >10 years outdoors, no degradation

Efficiency status:	Cell	18.8
	Submodule	14.7
	Module	12.1
	Commercial	>10
Others:	Stainless steel substrate	17.5
	Electrodeposition	15.4
	With ZnO (no buffer)	15.0

- Alloying with Ga and S; role of Na
- Progress mostly empirical; little understanding of materials/devices/processes

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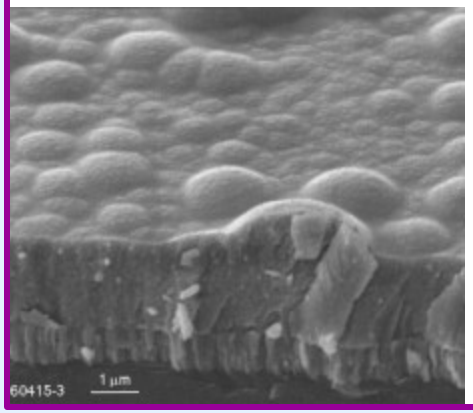
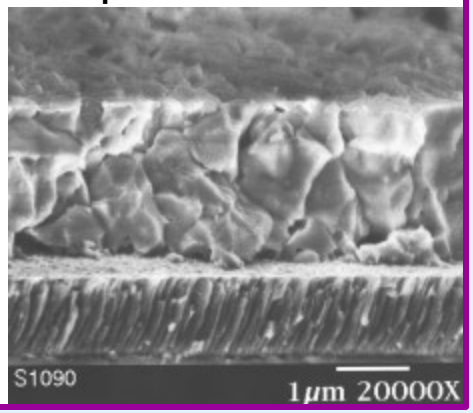
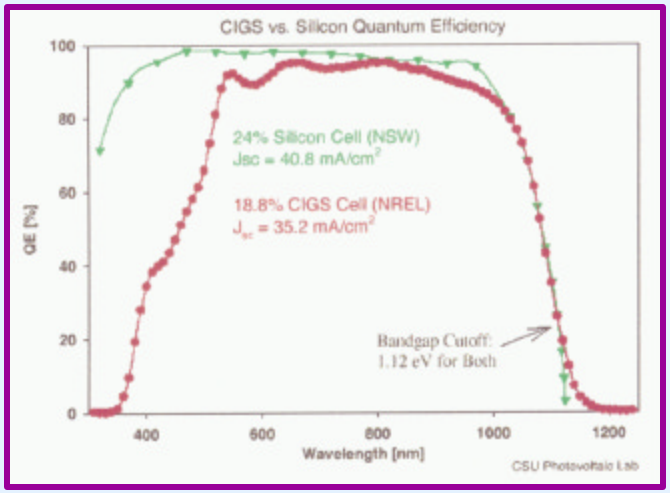
Thin-Film Copper Indium Diselenide (CIS) PV—Research Issues and Directions

Electrodeposited CIGS Precursor Film



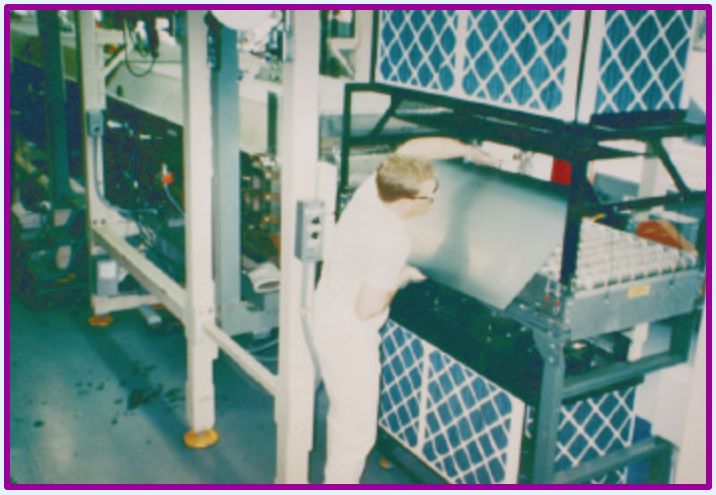
Absorber CIGS from Electro-deposited Precursor Film

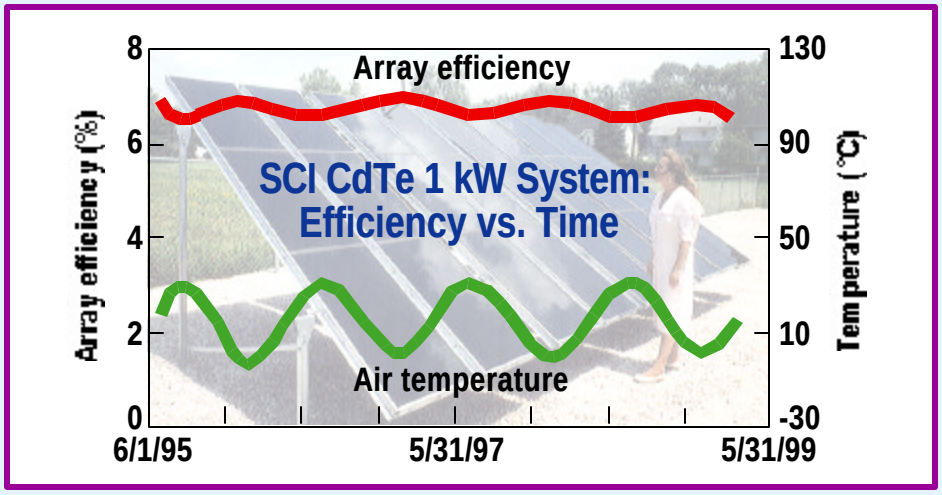




- Scalability of current processes
  - Predictive models of materials growth, devices, and processes
  - Real-time process controls
  - Yield and throughput
- New techniques and materials
  - Non-vacuum approaches
  - Low-temperature depositions
- Device research and development
  - Heterojunction vs. homojunction
  - Role of window materials; improvements in blue response
  - Alternate front and back contacts
  - Higher bandgaps and multijunctions
  - Device models and characterization
- Theory: Band structures, optoelectronic properties, defect physics, doping

Thin-Film Cadmium Telluride PV—Progress and Status





Key companies: First Solar, BP Solarex, Matsushita, Antec

- ~1 MW/year in consumer products
- Manufacturing expansions underway:
  - High-rate vapor transport (vacuum)
  - Electrodeposition (non-vacuum)
  - Few tens of MW in near term
- Field testing of modules shows promise

Efficiency status:

Cell	15.8
Module	10.8
Commercial	7–9

- Many approaches for >10% efficiency
- Lacking fundamental scientific and engineering base for materials/devices
- ES&H issues studied and under control (e.g., recycling)– Cd perception issue?

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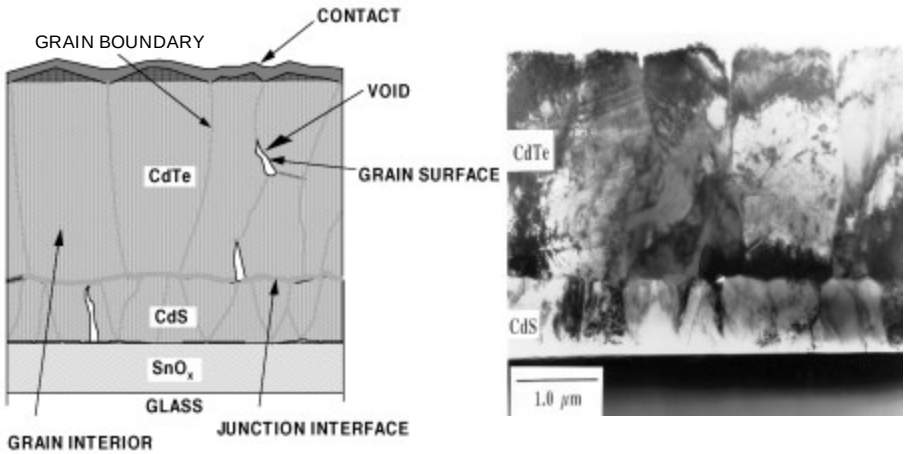
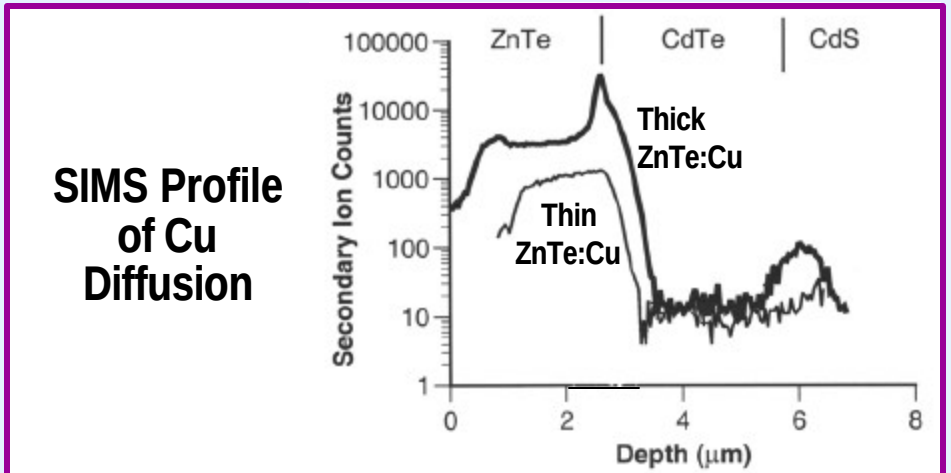
Thin-Film Cadmium Telluride PV—Research Issues and Directions





- Film deposition development
  - Nucleation and growth
  - Gas-phase or surface chemistries
  - Annealing and heat treatment ($CdCl_2$)
  - Grain growth, native defects, dopants
  - CdS/CdTe interdiffusion
  - Alternate transparent conductors; impact on film growth
- Successful first-time manufacturing

- Front and back contacts
  - Alternate transparent conductors
  - Low resistance, stable back contacts
  - Role of Cu; Cu-free contact strategies?
- Close efficiency gap (cell –> module)
- Compatibility of manufacturing process steps (e.g., tie to glass float-line?)
- Low-cost module packaging for long-term reliability (>20 years)
- Accelerated module test procedures

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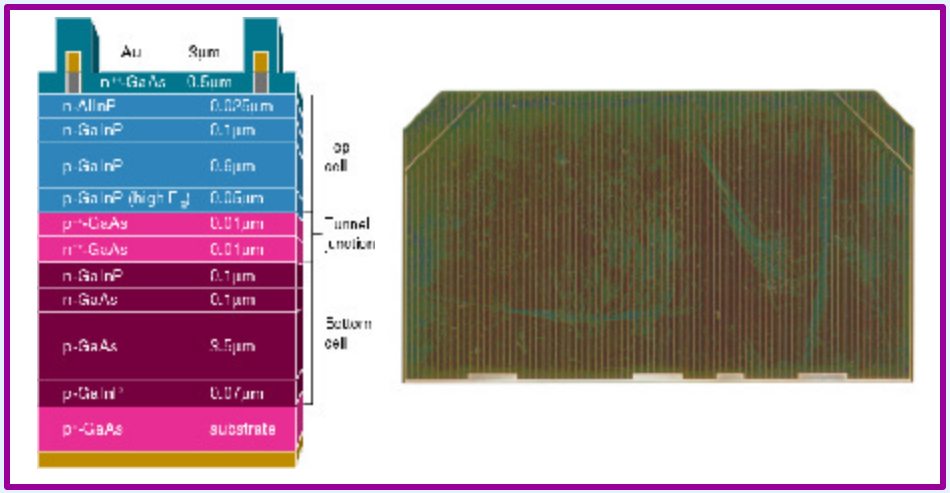
High-Efficiency and Concentrator PV—Progress and Status



Key companies: PV International, Entech, Amonix, Sunpower, Tecstar, Spectrolab, Honda, BP Solar

- Manufacturability demonstrated
  - Low-concentration, line focus
  - High-concentration, point focus
  - High efficiency cells (Si, GaAs, multijunctions) in production
- Limited applications in today's markets

Efficiencies:

Si (up to 400X)	27
GaAs (up to 1000X)	28
$GaInP_2$/GaAs (1X)	30.3
$GaInP_2$/GaAs (180X)	30.2
$GaInP_2$/GaAs/Ge (40–560X)	32.3

- Module efficiencies: 15-17% (Si); best prototypes: >20% (Si), >24% (GaAs), 28% ($GaInP_2$/GaAs/Ge at 10X)
- Large space markets drive $GaInP_2$/GaAs commercial cell production

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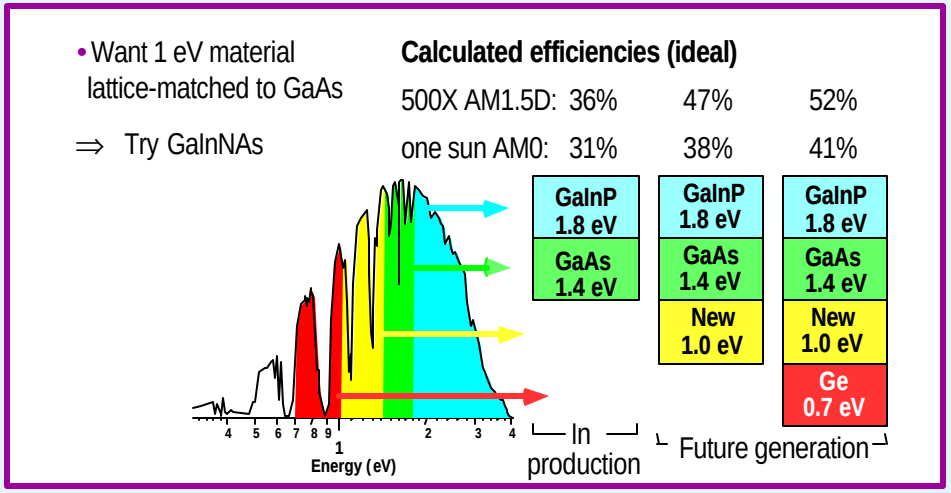
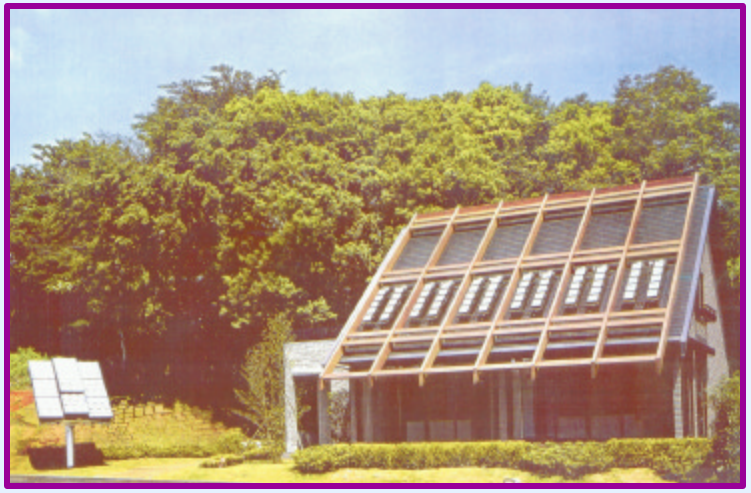
High-Efficiency and Concentrator PV—Research Issues and Directions

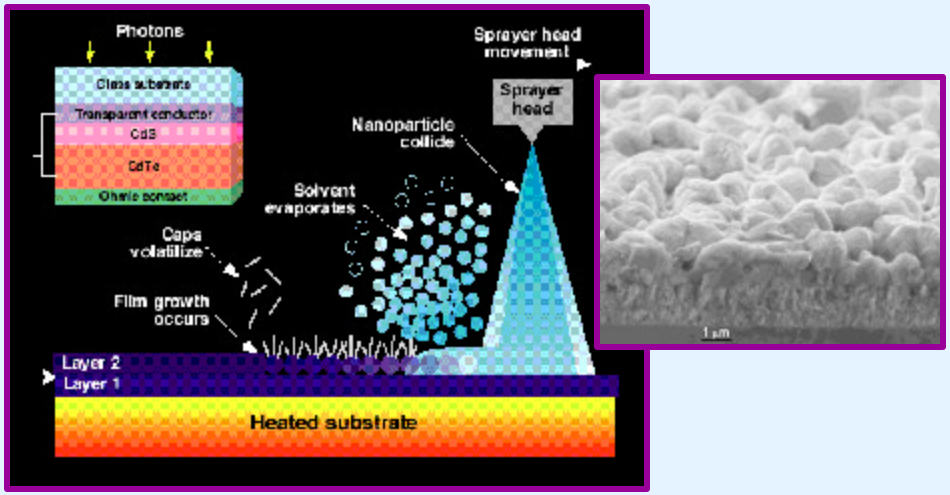


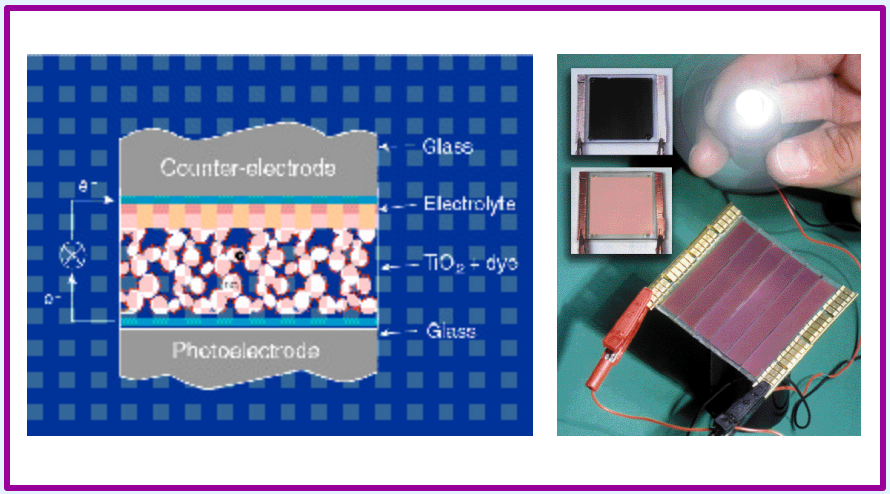


- High-efficiency (>40%) multijunctions
  - GaInAsN and Ge for 3rd and 4th cells
  - Lattice match to GaAs
  - Short diffusion lengths to date
- Monolithically integrated modules (e.g., for dish concentrators)
- New products for today's markets

- Novel concentrating concepts:
  - Reflecting troughs
  - Concentrating dish
  - PV/thermal hybrids
  - Non-imaging optics
  - Low-profile concentrators
- Standards for qualification and performance testing of concentrators

Novel PV Concepts and New Materials—Research Issues and Directions





Nanoparticle-derived precursors for PV

- Potential for very low cost
- Low process temperatures, non-vacuum
- Potential for smooth, dense films
- Absorbers (CdTe, CIS, ...)
- Transparent conductors (SnO_2, CdS, ...)
- Contacts (Ag, Au, Pt, ...)
- Nanocrystals, nanotubes, nanorods
- Nanocharacterization

Dye-sensitized TiO_2 photochemical cells

- Potential for very low cost
- Nanocrystalline TiO_2, with monolayer dye sensitizer, in liquid electrolyte
- 11%-efficient cell; scale-up for consumer products underway
- Dye stability issue
- Gel or solid-state electrolytes
- Photoelectrochromic window (with WO_3)

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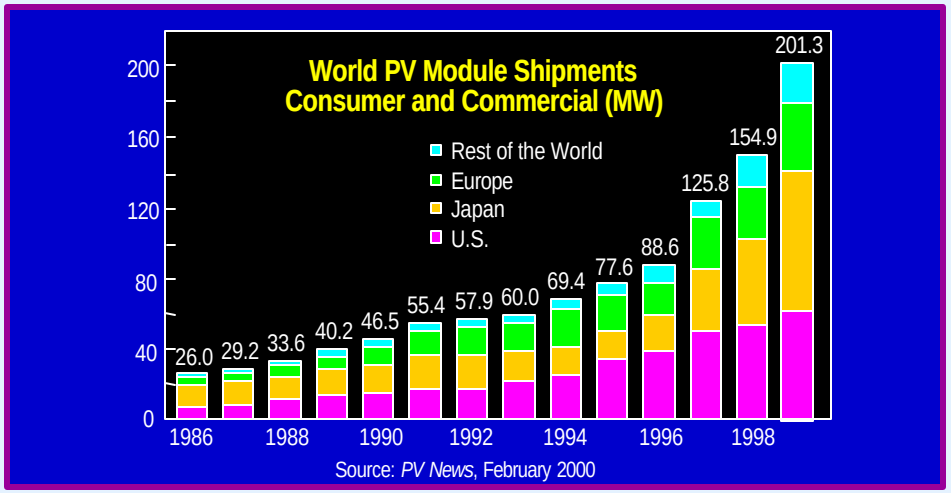
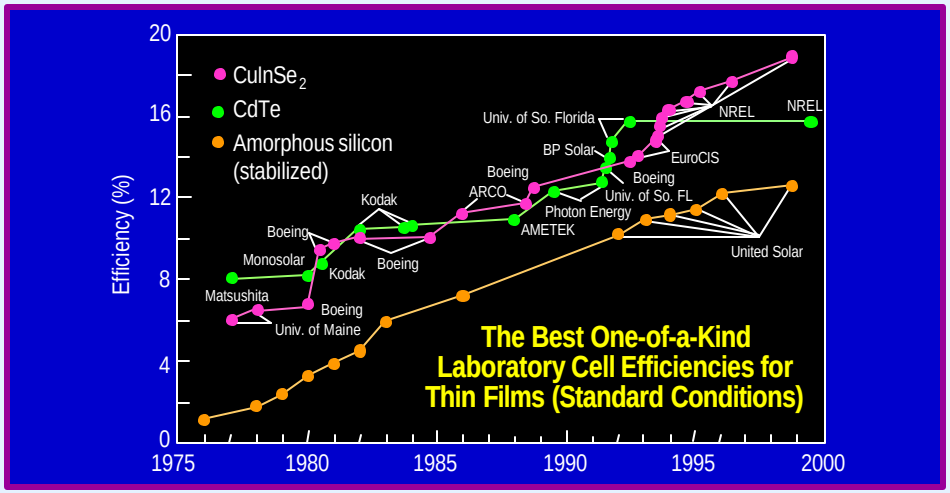
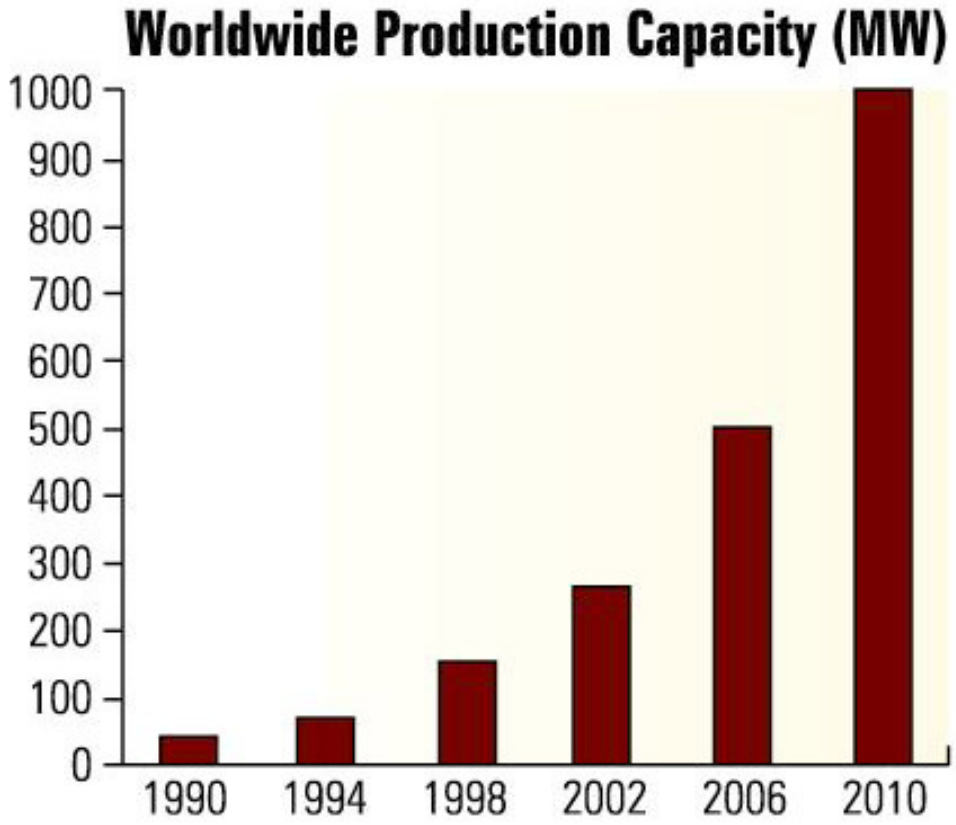
Photovoltaic Technology—Progress and Status

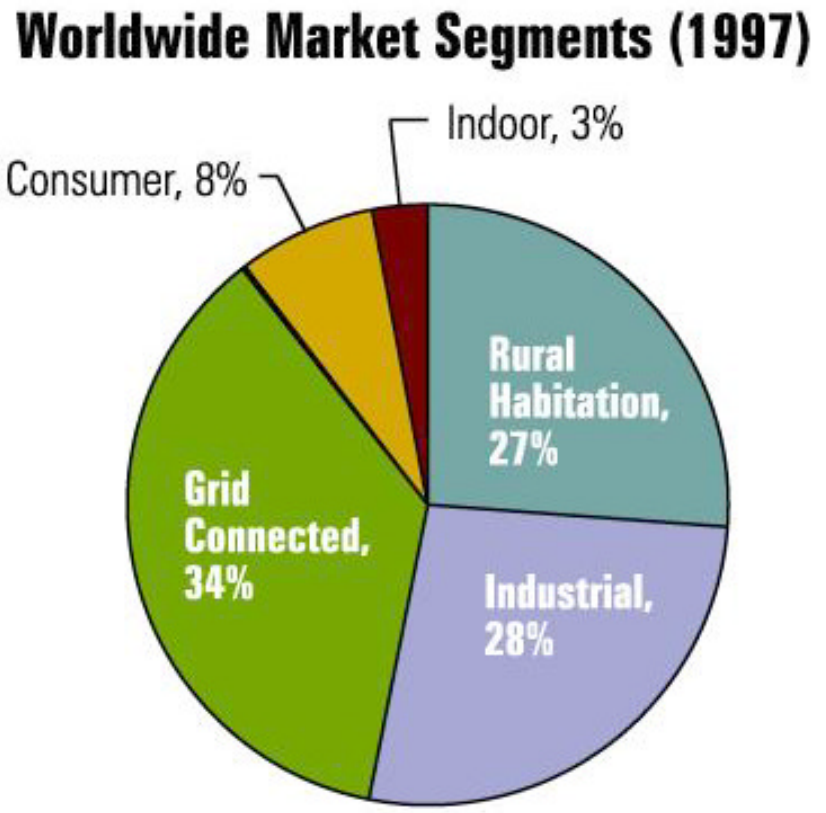


- World market (1999): 201.3 MW, ~$1.7 billion
- Average growth rate (1994–99): >20%
- Remote markets (telecommunications, developing countries); PV/buildings
- Module and system prices decreasing
- New products and applications
- Manufacturing capacities increasing: crystalline Si dominates, but thin film scale-up underway



- Record laboratory efficiencies, new materials, and innovations
- Commercial product efficiencies and reliability increasing
- **Multiple technology paths**
  - Crystalline silicon (ingot- and non-ingot-based)
  - Thin films (amorphous Si, CdTe, copper indium diselenide)
  - Concentrators and high efficiency





Source: Siemens Solar's web page

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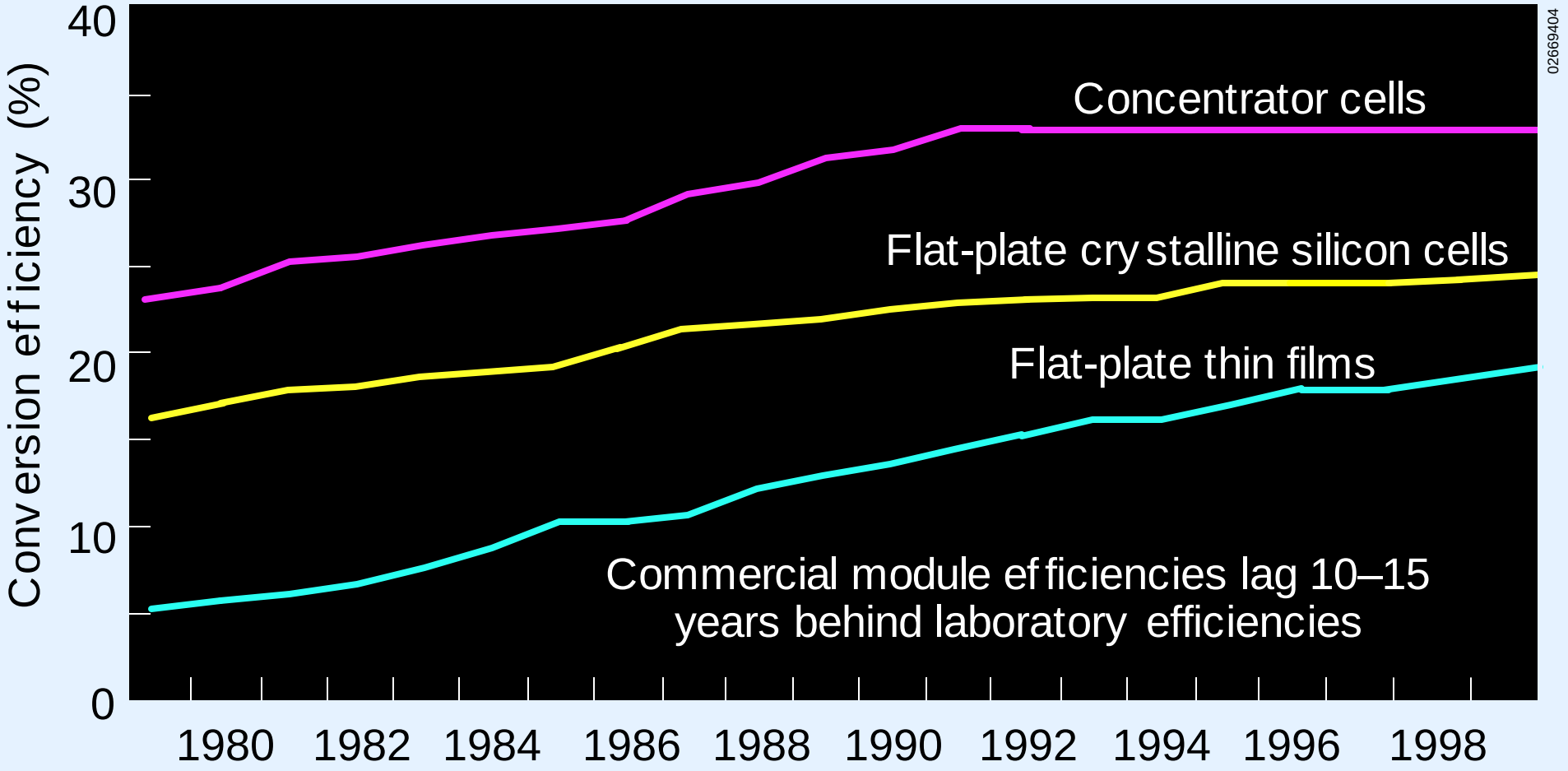
Progress in Laboratory Efficiencies



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Best Large-Area, Thin Film Modules
(Standard Conditions, Aperture Area)

Company	Device	Size (cm^2)	Efficiency	Power	Date
BP Solarex	CdS/CdTe	8681	8.3%	72 W	9/99
United Solar	a-Si triple junction	9276	7.6% (stabilized)	70.8 W	9/97
First Solar	CdTe/CdS	6728	9.1%	61.3 W	6/96
BP Solarex	a-Si dual junction	7417	7.6% (stabilized)	56 W	9/96
BP Solarex	CdS/CdTe	4874	10.8%	53.9 W	4/00
Matsushita	CdS/CdTe	5432	9.7%	52.7 W	12/99
Siemens Solar Industries	CdS/CIS-alloy	3651	12.1%	44.3 W	3/99
United Solar	a-Si triple	4519	7.9% (stabilized)	35.7 W	6/97
Golden Photon	CdS/CdTe	3366	9.2%	31 W	4/97

Revised 4/7/2000

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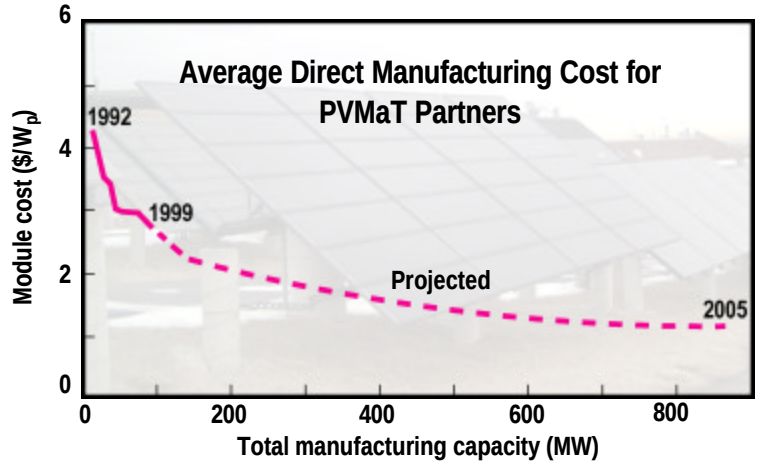
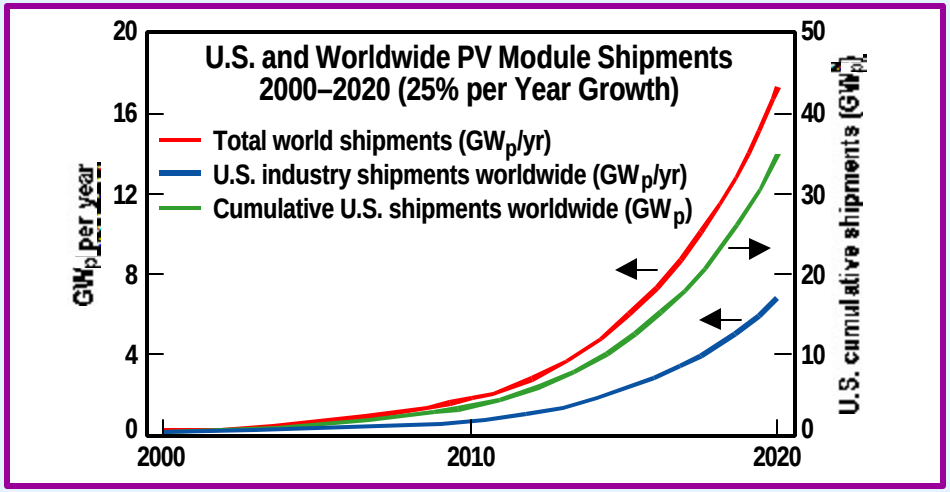
Photovoltaic Technology—Prospects and Future Directions





- PV works, reliable, competitive in many rapidly-growing markets
- Continuing technical advances: higher efficiencies and lower costs
- Significant manufacturing expansions underway: few 100s of MW in near term
- Crystalline silicon dominates markets
- Many challenges for new technologies: technical, market, and financial risks

- PV industry projection of 25% growth rate
- Significant contributions to energy and environment starting in 2020–2030
- Market incentives support manufacturing expansion, but impact on cost reduction not apparent
- Sustainable markets require lower cost technology
- Key: continued technology development

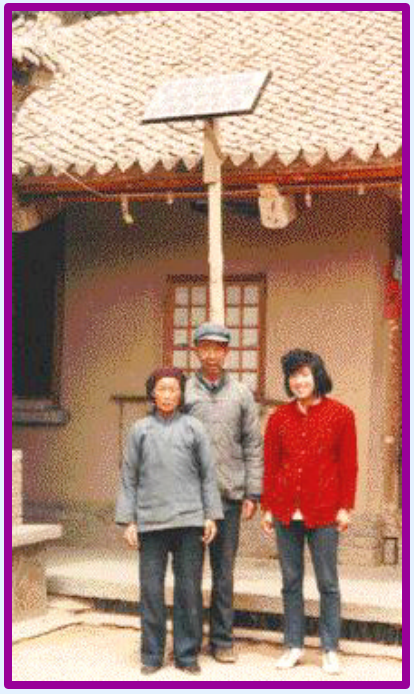
表二. 各區域人口, 離電力網路人口, 與PV裝置容量潛能

國家/區域 Country / Region	人口 Population (百萬人)	離電力網路人口 Off-Grid Population (百萬人)	PV容量潛能 Potential PV Capacity (MW, 百萬瓦)
非洲 (撒哈拉以南)	310	280	14,000
非洲 (撒哈拉以北)	135	56	3,800
東南亞洲及洋區	520	375	26,600
巴西	145	23	2,300
中國大陸	1,070	400	28,000
印度	770	600	42,000
印尼	175	80	9,800
墨西哥	80	20	800
蘇俄 (Russia)	280	5	550
中南美洲	190	40	5,250
中南歐洲	195	15	1,180

資料來源: Derek Lovejoy, "The Natural Sources Forum," May 1992, p. 102

PV裝設 in China

- > 100 Million people still have no access to electricity
- per Dr. Wang An-Hua (王安華？甘肅):
- supported by US-based Solar Electric Fund (SELF)
- 已裝置~2.9 MW (百萬瓦); 每年生產~4.5 MW



PV裝設 in China

Fortum PV systems provide power to Shenge Village in China at the altitude of 3600 metres

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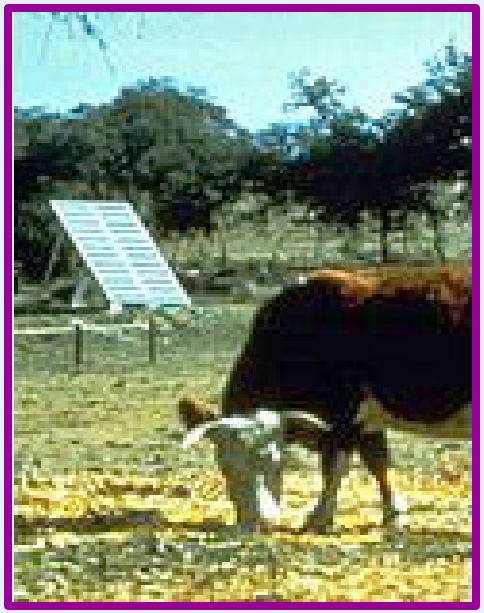

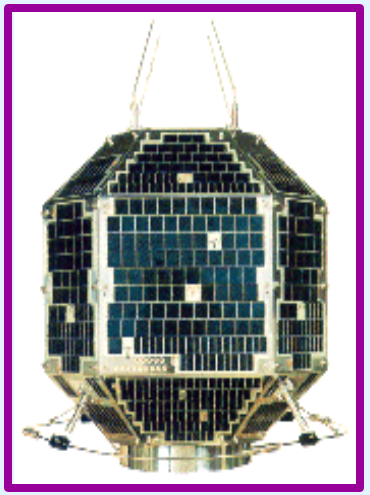

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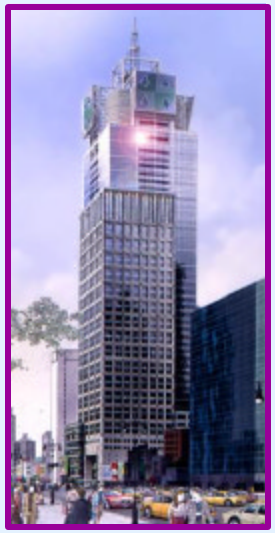
PV Markets and Applications — Buildings

Grid-connected:
Commercial and residential





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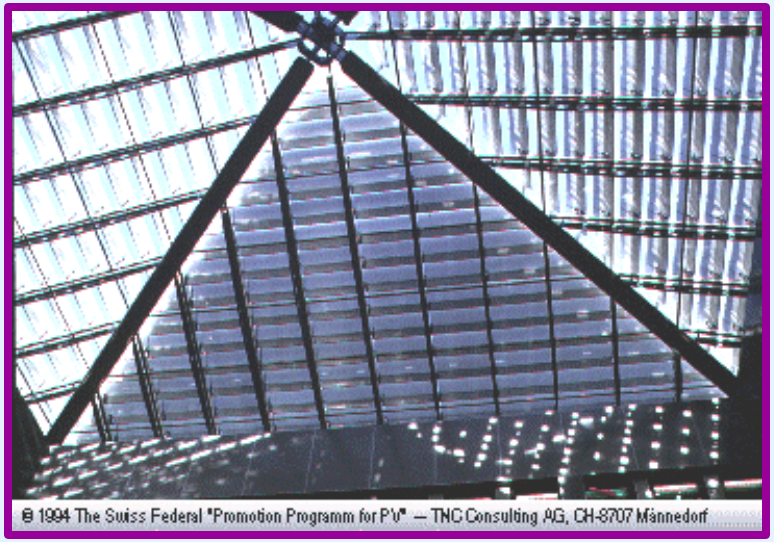

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PV Markets and Applications — Domestic

Remote, off-grid power:

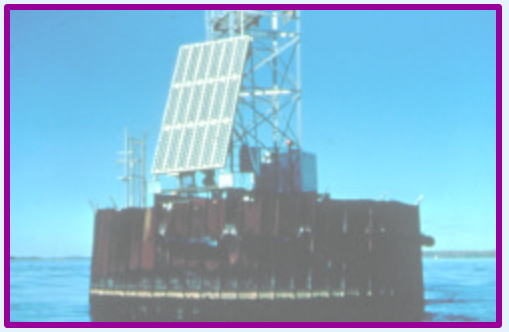
- Water pumping
- National Parks

- Stand-alone power
  - EV charging

PV Markets and Applications — Domestic

Remote, off-grid power:

- Telecommunications
- Signaling



- Disaster mitigation
- Emergency power

PV Markets and Applications — International

Rural electrification:

- Water pumping
- Desalination/disinfection

Brazil

India

China

India

Brazil

Home and security lighting

South Africa

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PV Markets and Applications — International

Zambia

Rural electrification:
Schools and clinics

South Africa

India

Brazil

Village power

Mexico